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The Agulhas Current System in the South Indian Ocean (Figure 1a) is one of the strongest western boundary current systems in the world due to its large volume transport (order 70 Sv) and high distribution of mean kinetic energy (up to 500 cm2/s2 in the northern Agulhas Current) (Lutjeharms, 2007). Downstream of the southwestward flowing Agulhas Current, the Agulhas Return Current (ARC) begins at the Agulhas retroflection in the southeast Atlantic and flows eastward in a quasistationary meandering pattern between 38o and 40o S (Boebel et al., 2003). Like the Agulhas Current, the ARC exhibits intense dynamics, strong mean currents, high levels of mesoscale variability and abundant eddy events (Lutjeharms and Ansorge, 2001). In addition, the close contact between subpolar and sub-tropical water masses in this region produces a strong frontal zone that is characterized by the presence of a strong temperature front and is manifested by interleaving thermohaline intrusions at submesoscales.

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Understanding Thermohaline Mixing in the Agulhas Return Current from Seismic and Finestructure Observations

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1 Introduction

The Agulhas Current System in the South Indian Ocean (Figure 1a) is one of the strongest western boundary current systems in the world due to its large volume transport (order 70 Sv) and high distribution of mean kinetic energy (up to 500 cm^2/s^2 in the northern Agulhas Current) (Lutjeharms, 2007). Downstream of the southwestward flowing Agulhas Current, the Agulhas Return Current (ARC) begins at the Agulhas retroflection in the southeast Atlantic and flows eastward in a quasi-stationary meandering pattern between 38^o and 40^o S (Boebel et al., 2003). Like the Agulhas Current, the ARC exhibits intense dynamics, strong mean currents, high levels of mesoscale variability and abundant eddy events (Lutjeharms and Ansorge, 2001). In addition, the close contact between sub-polar and sub-tropical water masses in this region produces a strong frontal zone that is characterized by the presence of a strong temperature front and is manifested by interleaving thermohaline intrusions at submesoscales.

In January-February 2012 the Naval Research Laboratory (NRL) and collaborators conducted a field experiment to examine frontal zone mixing processes at the quasi-permanent northward meander of the ARC in the vicinity of the Agulhas Plateau (Figure 1b). Velocity results from NRL's HYCOM model (Bleck, 2002) show that during the ARC12 cruise (January 23- February 8) a warm core anticyclone that had been located over the southeast portion of the Plateau moved westward and briefly merged with the ARC. Both seismic and traditional hydrographic observations were collected during the field experiment. Overall 8 seismic sections were acquired across the ARC, eddy, and zones in between and these were corroborated with simultaneous

XBT casts. The seismic observations were complemented by repeating the transects with 18 CTD stations, 37 casts from an Underway-CTD system (900 m profiles taken while traveling at 4 knots), and 41 microstructure casts to characterize turbulent mixing rates. Vessel-mounted ADCP data were acquired throughout the seismic and hydrographic surveys.

This study focuses on analyzing the seismic and hydrographic observations to elucidate submesoscale and fine scale frontal zone mixing processes by assessing how mesoscale and fine-scale features influence thermohaline interleaving and overall mixing processes in the study region.

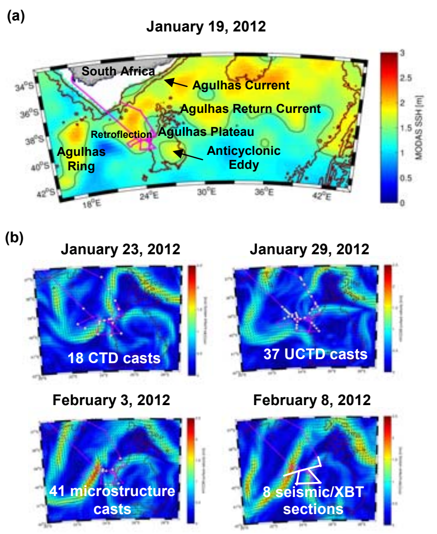

Figure 1. (a) Sea Surface Height (SSH) in the greater Agulhas System on January 19, 2012 as interpreted from satellite data using NRL's Modular Ocean Data Analysis System (MODAS) (Fox et al., 2002). This snapshot depicts the southward flowing Agulhas Current, the retroflection and Return Current, the presence of an anticyclonic eddy on the Agulhas Plateau, and an Agulhas ring west of the retroflection. (b). HYCOM velocity snapshots during the ARC12 cruise show a warm core anticyclone merging with the ARC. The cruise track and location of seismic sections and hydrographic stations are also shown.

2 The seismic oceanography method

The seismic oceanography method uses low-frequency (10-200 Hz) sound waves in the ocean water column to generate direct reflections off temperature contrasts. The generated reflections are then analyzed to identify water mass boundaries of fronts, eddies and oceanic fine structure on scales of meters to tens of meters (Ruddick et al., 2009). With a horizontal and vertical resolution approaching 10 m and data spanning from about 50 m depth to the seafloor, the technique yields band limited measurements of ocean reflectivity. Amplitude peaks and troughs in the measured seismogram can be traced horizontally for many 10s of kilometers. Strong temperature gradients produce strong reflectivity, which when convolved with the seismic measurement wavelet create alternating positive and negative values in the seismic image from single reflectors.

3 Results and discussion

During the ARC12 field experiment the high lateral resolution of the seismic observations allowed fine-scale lateral tracking of thermal intrusions and provided additional information about the submesoscales and finestructure not discernable by the hydrographic data alone. Figure 2 is an east-west seismic image collected during the cruise in the section that crossed both the northward flowing ARC and the southward flowing portion of the anticyclonic eddy (see Figure 1b). The vertical temperature

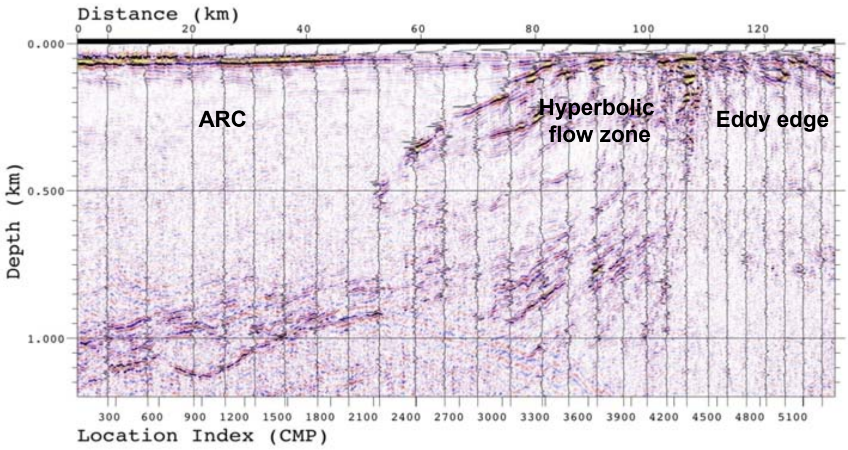

Figure 2. East-west seismic image acquired on February 1, 2012. In this section the northward flowing ARC in the vicinity of the Agulhas Plateau interacted with the southward flowing portion of a large warm-core anticyclonic eddy.

gradient fields derived from the XBT's are also plotted for comparison. Here the red (maximum at yellow) and blue (maximum at black) indicate positive and negative seismogram amplitude values, respectively. The interaction between the ARC and eddy is captured in these acoustic reflections, which are most prominent at the edge of a hyperbolic flow zone (small region of weak currents in between two strong currents directed in opposite directions) between the eddy edge and ARC. There, sub-polar waters interact with waters of sub-tropical origin on either side. Reflectors are shallow within the hyperbolic zone, but extend for many tens of km away from the zone, reaching to depths of 1100-1200 m underneath the ARC.

Analysis of Temperature-Salinity (TS) curves from the entire hydrographic dataset and specifically from CTD casts taken in the ARC, hyperbolic zone and eddy a day prior to the seismic section reveal the nature of the water mass boundaries associated with the observed seismic reflectors in Figure 2. The water column in the ARC features warm ($\leq 25^{o}C$) surface water above 200 m and a distinct subsurface salinity maximum associated with South Indian Subtropical Water. In the frontal region between the ARC and the eddy interleaving is evidenced by the presence of strong temperature and salinity gradients, particularly between 200-800 m depth. In this frontal zone concurrent with the hyperbolic zone, the characteristic salinity maximum at 200 m no longer exists and the surface water within the front is colder and fresher than in the ARC (Figure 3). A spatial map of salinities from hydrographic data along an isopycnal reveals that this fresh water may be from subpolar origin and entrained from the southwest. At the eddy edge TS characteristics are a combination of TS curves in the ARC and TS curves in the frontal region and indicate that the eddy was likely spawned from the ARC at an earlier time before travelling to the west and interacting with newer ARC waters.

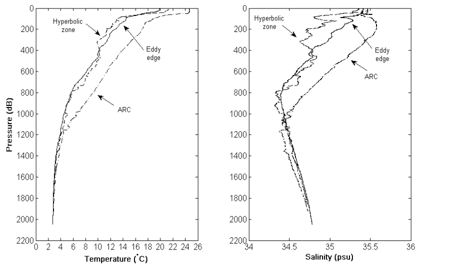

Figure 3. Temperature and salinity profiles from CTD casts in the ARC, hyperbolic flow zone and eddy edge taken on January 31, 2012 along the seismic transect shown in Figure 2.

An analysis of a separate seismic survey of a radial crossing of the eddy (i.e. the most southern east-west section on Figure 1b; not shown) combined with simultaneous XBT profiles confirms a thermal structure similar to the ARC and reveals that seismicly measured structures underneath the circulation core and outer edge of the eddy are formed by thermal intrusions that change in shape, size, strength and depth over 10s of km along the section. In addition seismicly measured signatures on this section are observed to vary according to thickness of the intrusion due to the convolution of the seismic measurement wavelet.

Analysis of consecutive XBT casts on the seismic eddy radial crossing transect (not shown) suggest that horizontal tracking of seismogram amplitude peaks and troughs do generally trace connected thermal intrusion features. However along the seismic transect that crosses the ARC, hyperbolic zone, and eddy edge (Figure 2), we find less connectivity between thermal intrusion structures in consecutive XBT casts, particularly near the hyperbolic zone. We speculate that vigorous mixing dynamics in this region, particularly in the localized region of the hyperbolic zone, caused thermal intrusion features to be mixed away over horizontal spatial scales smaller than our typical measurement spacing (5 km) of XBTs there. To assess the level of mixing during the seismic survey we used a method by Holbrook et al. (2013) whereby turbulent dissipation of kinetic energy (ε) is estimated from seismic horizontal wavenumber spectra. However, the signal-to-noise ratio of our data (acquired by a medium-sized, two GI-gun system), was insufficient for this analysis. Microstructure profiles acquired in the hyperbolic zone at a different time however yield estimates of ε as high as 10^{-7} W/kg^{-1} within the top 100 m of the water column, which suggests the presence of active turbulence in the frontal zone. A further horizontal wavenumber spectral analysis of the vessel-mounted ADCP data acquired during the seismic section reveals the presence of internal waves in the region and suggests that the elevated turbulent dissipation rates may be due to these dynamics.

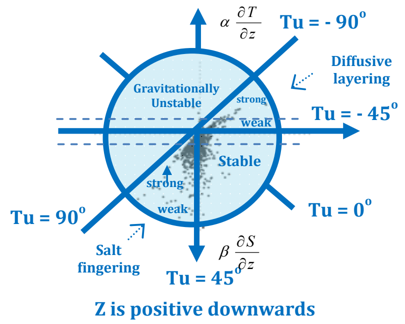

Figure 4. Temperature and salinity from CTD data collected during the ARC12 cruise plotted on the ∂T/∂z and ∂T/∂z plane. α and β are thermal and haline expansion coefficients, respectively. The horizontal dashed lines indicate rough estimates of the seismic estimated detection limits. For further details on the Turner angle method see Ruddick (1983).

A Turner angle analysis employs vertical temperature and salinity gradients to quantify the relative role these gradients contribute to the density gradient. Therefore Turner angles are practical indicators of water column stability to double-diffusive activity (Ruddick, 1983). A Turner angle plot (Figure 4) computed from hydrographic data can also be used for indicating the detectability of temperature gradients by the seismic method in a particular study area, and can help reveal the nature of the thermohaline intrusions present. The seismic method is sensitive to vertical temperature gradients in the water column, but the wavelet measurement convolution combines data together over > 40 m in the vertical and therefore small scale gradients in temperature that are weak become indistinguishable in the seismic measurements.

For our seismic observations in this study we estimate a rough detection limit to be of the order of 0.04^{o}C per meter. The horizontal dashed lines on Figure 4 indicate these rough estimates of the detection limits, however it should be pointed out that all data above or below both sets of lines cannot be detected by the seismic method because detection is a function of the vertical profile of dT/dz in addition to the strength of dT/dz at any given point. In addition, it is important to note that due to the thermal gradient detection constraint, the seismic method is better able to detect data occurring in the stable (Turner angles -45^o to 45^o), and salt fingering regimes (Turner angles 45^o to 90^o) than the diffusive layering regime (Turner angles -45^o to -90^o). In the ARC2 CTD dataset temperature gradients $\geq$ 0.04^{o}C per meter (see data outside the dashed lines in Figure 4) data mostly occur in the salt fingering regime, with a smaller subset occurring in the diffusive layering regime, indicating that the seismic method was able to detect strong temperature gradients from these data. We speculate the gradients conducive to salt fingering in the study area were produced as a result of warm and salty SISW waters existing above colder and fresher waters below in the ARC, while diffusive layering gradients were produced as a result of interleaving.

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